TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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TESTS OF ALUMINUM-ALLOY STIFFENED-SHEET SPECIMENS CUT FROM AN AIRPLANE WING

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SUMMARY

The specimens used in the present tests were cut from an actual airplane wing of the stressed-skin type. The specimens thus obtained were not representative of the usual type of laboratory specimens because the stiffeners were not exactly parallel nor evenly spaced and, in one case, the skin consisted of pieces of sheet of different thicknesses. The test data obtained indicate that the buckling strain of stiffened curved sheet can be computed with reasonable accuracy by the equation given by Wenzek. The ultimate loads of the specimens when tested as flat sheet were within ±11 percent of the product of the compressive yield strength and the cross-sectional area of the stiffeners. A rivet spacing equal to 98 times the sheet thickness was a source of weakness, and rivet spacings up to 36 times the sheet thickness appeared satisfactory.

INTRODUCTION

The aluminum-alloy stiffened-sheet specimens used in these tests were representative of members actually used in the stressed-skin type of construction. The information obtained from these specimens should be of value in interpreting the results of tests of laboratory specimens for design purposes.

The object of this investigation was to obtain information on the strength and behavior of aluminum-alloy stiffened-sheet specimens of the proportions actually used in airplane construction and to study the effects of curvature on the elastic buckling strength of thin sheet by means of successive tests of one specimen using templets of various radii. The specimens were tested to failure as stiffened flat sheet.

DESCRIPTION OF SPECIMENS

The six specimens obtained from the airplane wing are described in figures 1 to 4. In specimens A and B the skin consisted of three and two pieces of sheet, respectively, with lap splices at stiffeners as shown. After a number of tests of specimen A with various radii of curvature and with stresses in the elastic range, the two edge panels were removed, leaving a specimen with five stiffeners and the four intermediate panels of specimen A. This specimen was designated A'. Two of the four stiffeners of specimen C were extruded bulb angles and the other two were formed of alclad 24S-T sheet. The details of these formed angles are given in figure 3. Along the extruded edge stiffener, there was the overlapping sheet of a splice. Specimens D, E, and F, were taken from an aileron and consisted of a piece of sheet with a single extruded 24S-T bulb-angle stiffener attached to the longitudinal center line of the sheet.

Before testing, the ends of the specimens were finished flat and parallel in a milling machine. The degree of parallelism of the ends is indicated by the tolerance of 0.002 inch in the lengths of various elements of the sheet and stiffeners. In specimen A, the end surfaces were made normal to the middle stiffener and, in specimens B and C, they were normal to one of the intermediate stiffeners. Of course, in specimens D, E, and F the end surfaces were normal to the single stiffener.

METHOD OF TEST

The stiffened-sheet specimens were tested between the fixed heads of an Amsler testing machine of the hydraulic type having a maximum capacity of 300,000 pounds. The smallest load range of 30,000 pounds was used. Before the tests, the platens of the testing machine were alined practically parallel, under zero load, by means of the special leveling rings in the lower head. These leveling rings, which were developed and built at the Aluminum Research Laboratories in 1938, may be seen directly below the lower platen in figures 5 and 6. The distance between the bearing surfaces at the four corners was measured by a 0.001-inch dial gage. At the ends of one diagonal of the 24-inch-square platens, the variation in distance between the platens was only 0.0001 inch; whereas, at the ends of the other diagonal, the variation was about 0.002 inch. This lack of parallelism was not considered objectionable in these tests because the lack of parallelism of the ends of the specimens was also of this order of magnitude. The specimens were placed in the testing machine in such a way that the lack of parallelism of the ends of the specimens compensated for that of the platens.

For those tests in which the specimens were loaded as stiffened flat sheets, straight bars were clamped to the platens and the specimens in turn were clamped against these bars. Figure 5 shows specimen A in the testing machine ready for the test as a stiffened flat sheet.

For those tests in which the specimens were loaded as stiffened curved sheets, templets of the desired radius were clamped to the platens of the testing machine and the specimen was sprung elastically to fit the templets. This arrangement is illustrated in figure 6. A face of the holding blocks was turned to the correct radius and slotted to fit over the stiffeners, pressing the sheet against the templet. In order to obtain a satisfactory fit with the smaller radii, it was necessary to use more holding blocks than the one pair shown in figure 6.

Longitudinal strains were measured on both sides of the specimens at a number of gage lines along the transverse center line by type A Huggenberger Tensometers using a 1-inch gage length. The magnification ratio of these instruments is about 1200, which gives an estimated strain measurement corresponding to a stress of about 80 pounds per square inch. It is realized that the measurement in only the longitudinal direction is insufficient to determine the stress in the sheet, but it was previously found that the average stress could be determined from the average of the strains on the two sides of the sheet. Furthermore, inasmuch as it was decided to deal with critical buckling strains and not stresses, it appeared that the one measurement should be sufficient. Because the strains could not be measured simultaneously on all the gage lines, it was necessary to load the specimen a number of times, keeping the stresses within the elastic stress range.

Specimen A was tested a number of times, first as a flat sheet and then as a curved sheet using radii corresponding to radius-thickness ratios of about 2000, 1500, and 1000. Because the buckling strengths of the sheet in these conditions were all in the elastic stress range, no permanent sets were developed. The width of the specimen was then reduced to approximately 21 inches by removing the two outside stiffeners and panels. Specimen A' was then tested as a flat sheet, with a radius-thickness ratio of 1000, and finally to failure as a flat sheet.

RESULTS AND DISCUSSION

Typical relationships between the load and the measured longitudinal strains are shown in figures 7 and 8. As stated previously, it was thought advantageous to consider critical strains rather than critical stresses because of the combination of alloys used; namely, 24S-T extruded stiffeners and sheet, alclad 24S-T sheet, and alclad 24S-RT sheet. For the low stresses encountered, there might not have been any question about the value of the modulus of elasticity but, by considering strains, that question cannot arise except in the computation of the average strain P/AE. Because the comparison of this computed average strain with the measured strains is relatively unimportant, the question of the value of the modulus of elasticity is not serious.

The average of the measured strains is given for those stations at the middle of the sheet panels. It will be noticed that in nearly every case this curve of average measured strain indicates a maximum value of strain that can be developed in the sheet. The maximum value of the average strain will be referred to as the measured critical strain. Values of measured critical strain for all the specimens are given in tables I and II.

For the specimens tested as stiffened flat sheet, the critical buckling strain can be computed by the equation (reference 1)

$$\epsilon_c = \frac{\sigma_c}{E} = \frac{k}{1 - \mu^2}\left(\frac{t}{b}\right)^2 \qquad (1)$$

in which

ϵ_c critical buckling strain, inches per inch

σ_c critical buckling stress, pounds per square inch

E modulus of elasticity, pounds per square inch k coefficient depending on support at edges of sheet panel and on proportions of sheet panel

μ Poisson's ratio

t thickness of sheet, inches

and

b unsupported width of sheet, inches

With a very few exceptions, the measured critical strains fall between the two limiting values of critical strain computed for the conditions of simply supported edges and for built-in edges. This comparison is shown in table I.

Figure 9 shows the load-strain relationships for gage line 10 of specimens A and A'. The influence of the curvature on the measured critical strain and on the load at which the measured critical strain was developed is apparent. A noticeable difference in the behavior of the specimens was noted in that the suddenness of the buckling increased as the radius of curvature decreased. As indicated in figure 9, the load at which the measured stress in the flat panel was developed is not well defined. The buckle formed at a low load and increased in size with no definite buckling action. With decreasing radii, the definiteness of the load at buckling increases. With a radius of curvature of 46.5 inches, the buckle occurred with such violence that the Tensometers were jarred and additional readings at higher loads could not be taken. The buckles vanished rather violently under decreasing loads. This cycle of buckling and returning to the original curved condition was repeated a number of times.

The effects of curvature on the measured critical strains are indicated in figure 10. Except for gage line 2, which was in an exterior panel, the data points agree reasonably well with the straight-line relationship expressed by the Wenzek formula (reference 2)

$$\epsilon_c = \frac{\sigma_c}{E} = 5\left(\frac{t}{b}\right)^2 + 0.3\left(\frac{t}{R}\right) \qquad (2)$$

in which R is the radius of curvature and the other terms are previously defined. The first term on the right will be seen to have the same form as the right-hand member of equation (1); whereas the second term shows the effects of the curvature. The use of the factor 5 in the first term gives the buckling strain in a flat sheet panel with a slight amount of restraint along the edges which are not loaded. The amount of this restraint is indicated by the position of the intercept on the axis of critical strain relative to the two limiting values of computed critical strain.

Also shown with the data in figure 10 is the curve of the equation (reference 3)

$$\epsilon_c = \frac{\sigma_c}{E} = \frac{1}{6(1-\mu^2)}\left\{\sqrt{12(1-\mu^2)\left(\frac{t}{R}\right)^2 + \left(\frac{\pi t}{b}\right)^4} + \left(\frac{\pi t}{b}\right)^2\right\} \quad (3)$$

in which the terms have been previously defined. This equation can be reduced to the following form which is quite similar to that of equation (2)

$$\epsilon_c = \frac{\sigma_c}{E} = \frac{\pi^2}{6(1-\mu^2)}\left(\frac{t}{b}\right)^2 + \sqrt{\left[\frac{\pi^2}{6(1-\mu^2)}\left(\frac{t}{b}\right)^2\right]^2 + \frac{1}{3(1-\mu^2)}\left(\frac{t}{R}\right)^2} \quad (3a)$$

For the case in which the effects of $\frac{t}{R}$ are small in comparison with those of $\frac{t}{b}$, this equation reduces to that obtained for a flat panel with simple support on all four edges. Consequently, in figure 10, the curve intersects the axis of critical strain below the value of the critical strain computed for flat sheet with simple support along the edges which were not loaded and complete fixation along the loaded edges.

For the case in which the effects of $\frac{t}{b}$ are small in comparison with those of $\frac{t}{R}$, this equation reduces to that obtained for a complete cylinder which appears to predict values of critical buckling stress two or more times greater than most test results (reference 4). For large values of $\frac{t}{R}$, the curve approaches a straight line, the slope of which is about twice as great as that of equation (2). The test data in figure 10 indicate that the effects of the term involving $\frac{t}{R}$ are too great. It is suggested by Schapitz and Krümling (reference 5) that the effects of this term be reduced to correspond to a critical buckling stress for a complete cylinder given by the equation

$$\sigma_c = 0.2E \frac{t}{R} \qquad (4)$$

in which the terms are previously defined. This suggestion leads to a slope only two-thirds that of equation (2) and less than that indicated by the trend of the data in figure 10.

In reference 3, a comparison is made of predicted critical stresses (equation (3)) and failing stresses for some stiffened curved panels. The predicted critical stresses were less than the failing stresses, the ratios ranging from 0.332 to 0.950. Such a comparison is misleading because, for large ratios of $\frac{R}{t}$ with stiffened specimens, buckling and failure are quite different phenomena. The ratios of the strengths will vary considerably with the proportions of stiffeners and sheet.

The ultimate loads and the average stresses at failure for the specimens tested as flat sheet are given in table III.

In specimen B the centers of the outstanding legs of the extruded stiffeners deflected noticeably in the direction parallel to the sheet at a load of 13,500 pounds; whereas the ultimate load was 16,475 pounds. After failure the shape of this edge was much like that of a column tested to failure with flat ends and the wave length was entirely independent of that of the sheet.

In specimen C the outstanding legs of the formed stiffeners showed some deflection parallel to the sheet at a load of about 7500 pounds; whereas the ultimate load was 12,975 pounds. The wave length of the outstanding edges of the sheet was approximately the same as the wave length of the buckle pattern in the sheet between the stiffeners; namely, about 5.5 inches. The extruded stiffeners of this specimen, unlike those of specimen B, developed a wave length nearly equal to that of the buckle pattern in the sheet. The lateral deflections of the outstanding legs of the extruded stiffeners were much smaller than those of the formed stiffeners.

The difference in the ultimate strengths of specimens B and C reflects the combined effects of the difference in sheet thickness and the difference in formed and extruded stiffeners.

The failure of specimen E was probably precipitated by the buckling of the sheet between rivets. As noted above, the rivet spacing was 98 times the sheet thickness. This action is at least partly responsible for the difference in the ultimate strengths of specimens E and F. The greater value of $\frac{b}{t}$ for specimen E also is probably partly responsible. Specimens D, E, and F, with a single stiffener, failed by twisting of the center relative to the ends.

In the design of structures of this type, it is usually assumed that only a portion of the sheet acts with the stiffeners and is effective in supporting the load. If it is assumed that failure occurs when the stress on the effective area equals the compressive yield strength of the material, the effective width of sheet panel between adjacent stiffeners can be determined by the equation (reference 6)

$$2b_e = Ct\sqrt{\frac{E}{\sigma_{yield}}} \tag{5}$$

in which

$2b_e$ effective width of sheet per panel, inches

C coefficient (theoretically varying from 1.24 to 1.90; taken here as 1.70)

and

σ_{yield} compressive yield strength of material, pounds per square inch

For specimens A', B, and C the effective areas are 0.593, 0.462, and 0.402 square inches, respectively. Based on a compressive yield strength of 44,500 pounds per square inch (88 percent of the average tensile yield strength of the stiffener material, (reference 7) the computed ultimate strengths are 26,400, 20,600, and 17,900 pounds. These values are from 19 to 38 percent greater than the test results given in table III. The use of 1.3 as the value of C in equation (5) reduces the excesses to about 14 and 33 percent.

It might also be assumed that the stress at failure is less than the compressive yield strength and that the effective width of sheet may be computed by the equation (reference 8)

$$2b_e = b\sqrt{\frac{\sigma_p}{\sigma_s}} \tag{6}$$

in which

b width of sheet panel between adjacent stiffeners, inches

σ_p critical buckling stress for sheet panel, pounds per square inch

and

σ_s stiffener stress or average stress on effective area, pounds per square inch

If the curve of column strength of the material is used to determine the value of σ_s, the ultimate load of a member can now be computed. The results of such computations for specimens A', B, and C are 26,300, 19,030, and 17,800 pounds, respectively. These values are from 16 to 37 percent greater than the test results given in table III.

A third assumption for computing the ultimate strengths is that no sheet is effective and the average stress at failure equals the compressive yield strength of the material. The strengths of specimens A', B, and C computed on this basis are 20,300, 16,100, and 14,150 pounds, respectively. These values as well as similar values for specimens D and F are within ±11 percent of the test results given in table III. The computed strength of specimen E is the only one differing appreciably from the test result (41 percent greater). It should be noted that the sheet of this specimen was the thinnest of the lot and that the rivet spacing was about 98 times the thickness of the sheet.

CONCLUSIONS

The following conclusions have been drawn from the data obtained from tests of stiffened-sheet specimens cut from an airplane wing and the discussion presented in the present report. The specimens consisted of 24S-T stiffeners, alclad 24S-T sheet, and alclad 24S-RT sheet. In the specimens with more than one stiffener the stiffeners were not exactly parallel.

1. The critical buckling strain of stiffened curved sheet in the elastic range varies linearly with the ratio of the thickness of sheet to the radius of curvature and can be computed with reasonable accuracy by the equation given by Wenzek.

2. The suddenness and violence of the buckling increases as the radius of curvature decreases.

3. For ratios of radius of curvature to thickness of sheet equal to or greater than 1000, the buckling of alclad 24S-T sheet is elastic. By alternately increasing and decreasing the load in a range including the buckling load, the buckle pattern can be made to snap into and out of the curved sheet.

4. A rivet spacing equal to 98 times the thickness of the sheet is a source of weakness. In specimens with a rivet spacing equal to or less than about 36 times the thickness of the sheet, the ultimate strength is not affected by the rivet spacing.

5. For the specimens with slenderness ratios between about 36 and 66 and with a rivet spacing of about 36 times the thickness of the sheet, the ultimate loads based on the stiffener area alone and the compressive yield strength of the material are within ±11 percent of the test results.

Aluminum Research Laboratories,
Aluminum Company of America,
New Kensington, Pa., November 19, 1942.

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TABLE I

CRITICAL BUCKLING STRAINS FOR STIFFENED FLAT SHEET

[Specimens cut from an airplane wing]

Specimen	Gage line	$\frac{b}{t}$	Measured critical strain	Computed Critical Strain*	
				Simply supported edges	Fixed edges
A	2	172	1.80×10^{-4}	1.48×10^{-4}	2.42×10^{-4}
	4	170	1.80	1.52	2.48
	6	177	.80	1.40	2.28
	8	175	1.30	1.40	2.28
	10	184	1.80	1.31	2.12
	12	168	2.60	1.52	2.49
A'	4	170	2.00	1.52	2.48
	6	177	1.40	1.40	2.28
	8	175	2.20	1.40	2.28
	10	184	1.80	1.31	2.12
B	2	170	1.75	1.38	2.31
	4	170	1.55	1.38	2.31
	6	171	1.90	1.36	2.28
C	2	155	3.20	1.61	2.72
	4	148	2.80	1.76	2.99
	6	169	1.70	1.37	2.31
D	1	132	.40	.445	.743
	5	132	.40	.445	.743
E	1	74	--------	.790	2.12
	3	74	1.40	.790	2.12
F	1	33.3	-------	3.59	10.40
	3	33.3	7.6	3.59	10.40

*Computed by equation (1) on the basis that the loaded edges are fixed.

TABLE II

CRITICAL BUCKLING STRAINS FOR STIFFENED CURVED SHEET

[Specimens cut from an airplane wing]

Specimen	Radius of curvature, R (in.)	Gage line	$\frac{R}{t}$	$\frac{b}{t}$	Measured critical strain (in./in.)
A	62	2	2067	172	1.20×10^{-4}
		4	2067	170	2.60
		6	2100	177	3.30
		8	2100	175	3.30
		10	2100	184	3.10
		12	2258	168	3.00
A	46.5	2	1550	172	1.70
		4	1550	170	3.50
		6	1577	177	4.00
		8	1577	175	4.30
		10	1577	184	4.20
		12	1691	168	3.40
A	31	2	1033	172	2.30
		4	1033	170	4.60
		6	1050	177	5.50
		8	1050	175	6.00
		10	1050	184	5.30
		12	1129	168	4.40
A'	31	4	1033	170	4.20
		6	1050	177	5.00
		8	1050	175	5.80
		10	1050	184	4.30

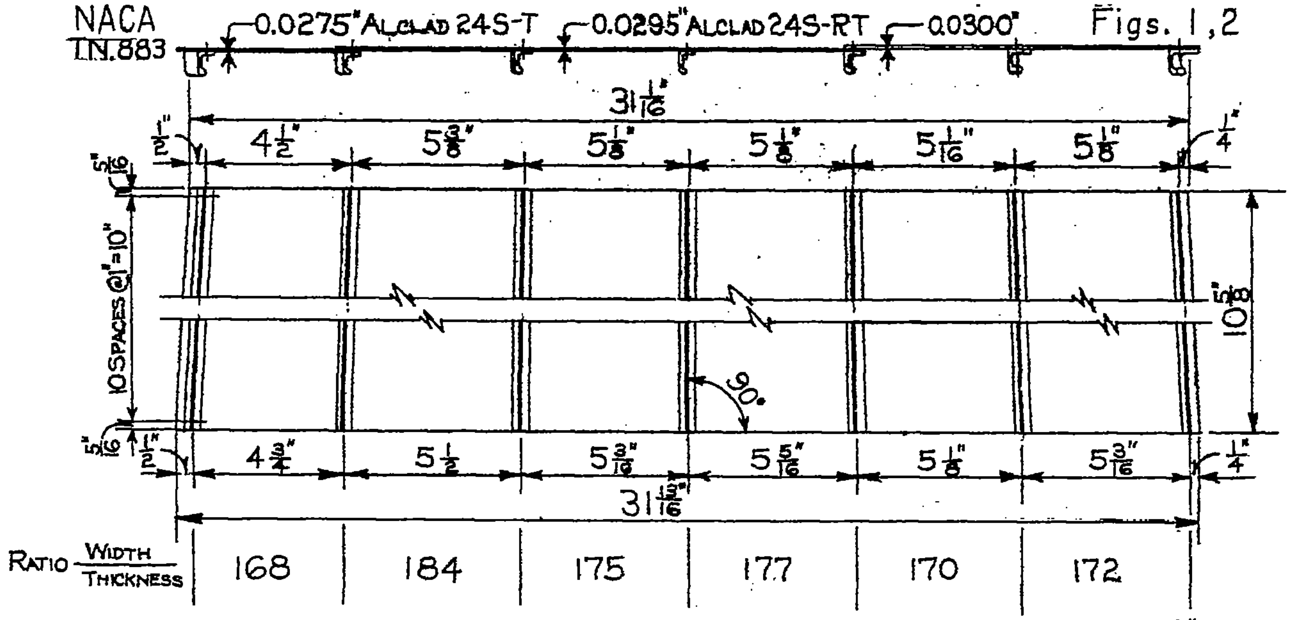
TABLE III

ULTIMATE STRENGTHS OF STIFFENED-FLAT-SHEET SPECIMENS

[Specimens cut from an airplane wing]

Specimen	Cross-sectional area,* A (sq in.)	Slenderness ratio,* L/P	Ultimate load, P (lb)	Average stress,* P/A (lb/sq in.)
A'	1.112	36.6	22,175	19,940
B	.858	54.1	16,475	19,200
C	.717	65.6	12,975	18,100
D	.333	50.7	4,100	12,310
E	.157	40.3	3,000	19,110
F	.152	38.8	3,600	23,680

*Assuming full width of sheet acting with the stiffeners.



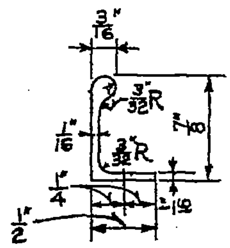


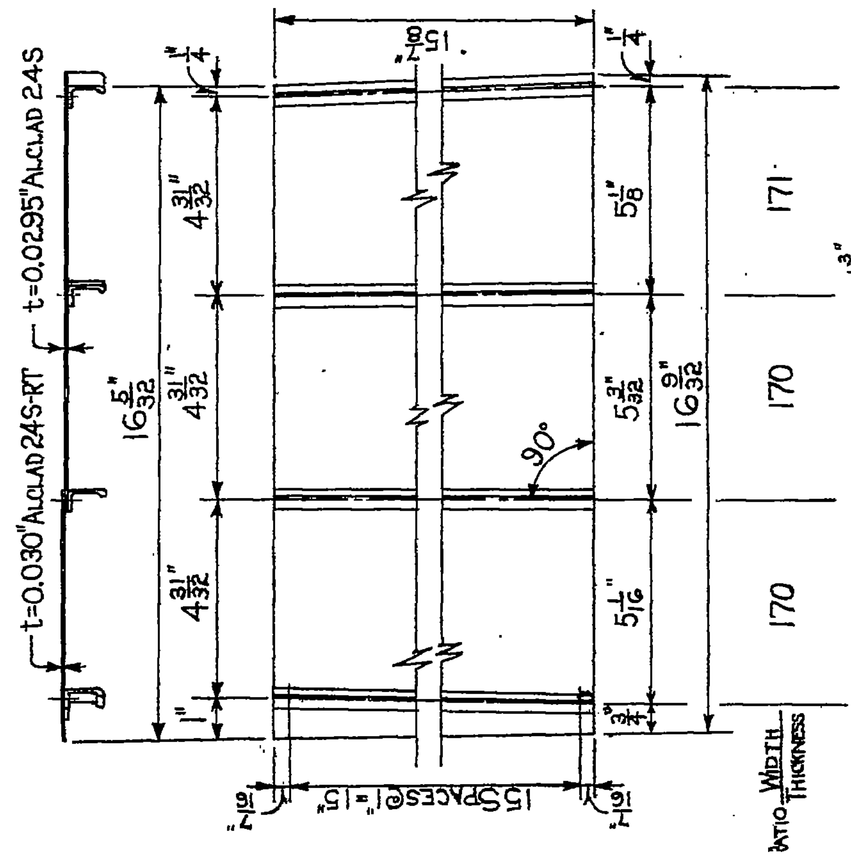
FIGURE 1.- SPECIMEN A (AS SHOWN)

CROSS-SECTIONAL AREA=1.574 SQ. IN.

SPECIMEN A' CONTAINS 5 STIFFENERS AND THE 4 INTERMEDIATE PANELS OF SPECIMEN A, CROSS-SECTIONAL AREA=1.112 SQ. IN.

STIFFENERS OF EXTRUDED 24S-T SHEET OF ALCLAD 24S

3/32" RIVETS -



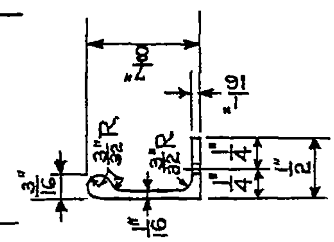


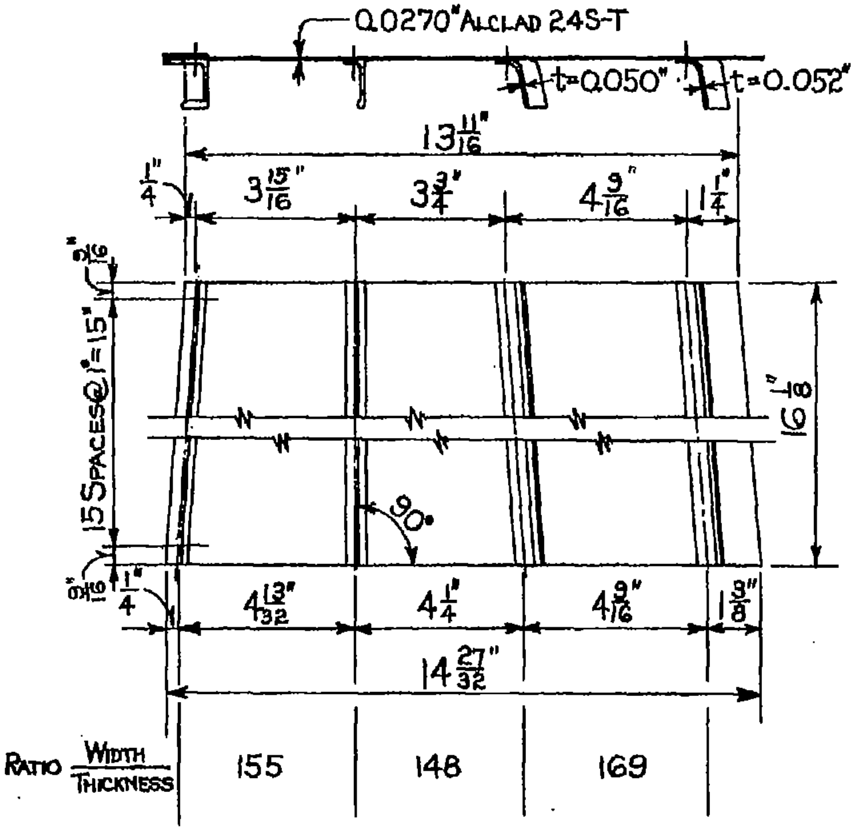
FIGURE 2.- SPECIMEN B

CROSS-SECTIONAL AREA=0.858 SQ. IN.

STIFFENERS OF EXTRUDED 24S-T

SHEET OF ALCLAD 24S

3/32" RIVETS



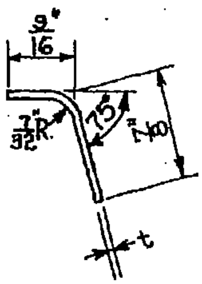


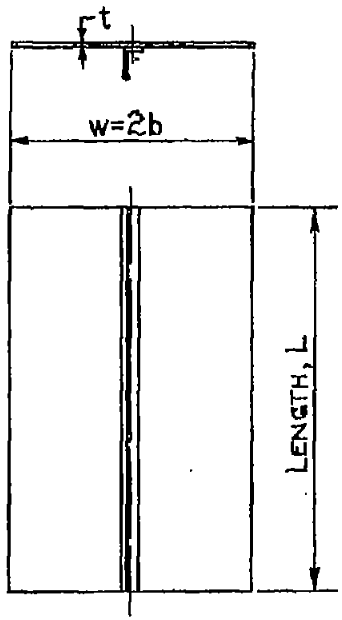
Figure 3.-Specimen C

Cross-sectional Area = 0.717 Sq.In.

Stiffeners of Extruded 24S-T & Alclad 24S

Sheet of Alclad 24S-T

3/32" Rivets



Specimen	Length, L in.	Width, W in.	Thickness, t in.	Area, A sq. in.	Rivet Spacing, in.	b/t
D	12.530	8 1/16	.0305	0.333	1	132
E	12.655	3 1/32	.0205	0.157	2	74
F	12.552	2 1/32	.0305	0.152	1	33.3

Figure 4.- Specimens D, E, and F. 3/32 Rivets.

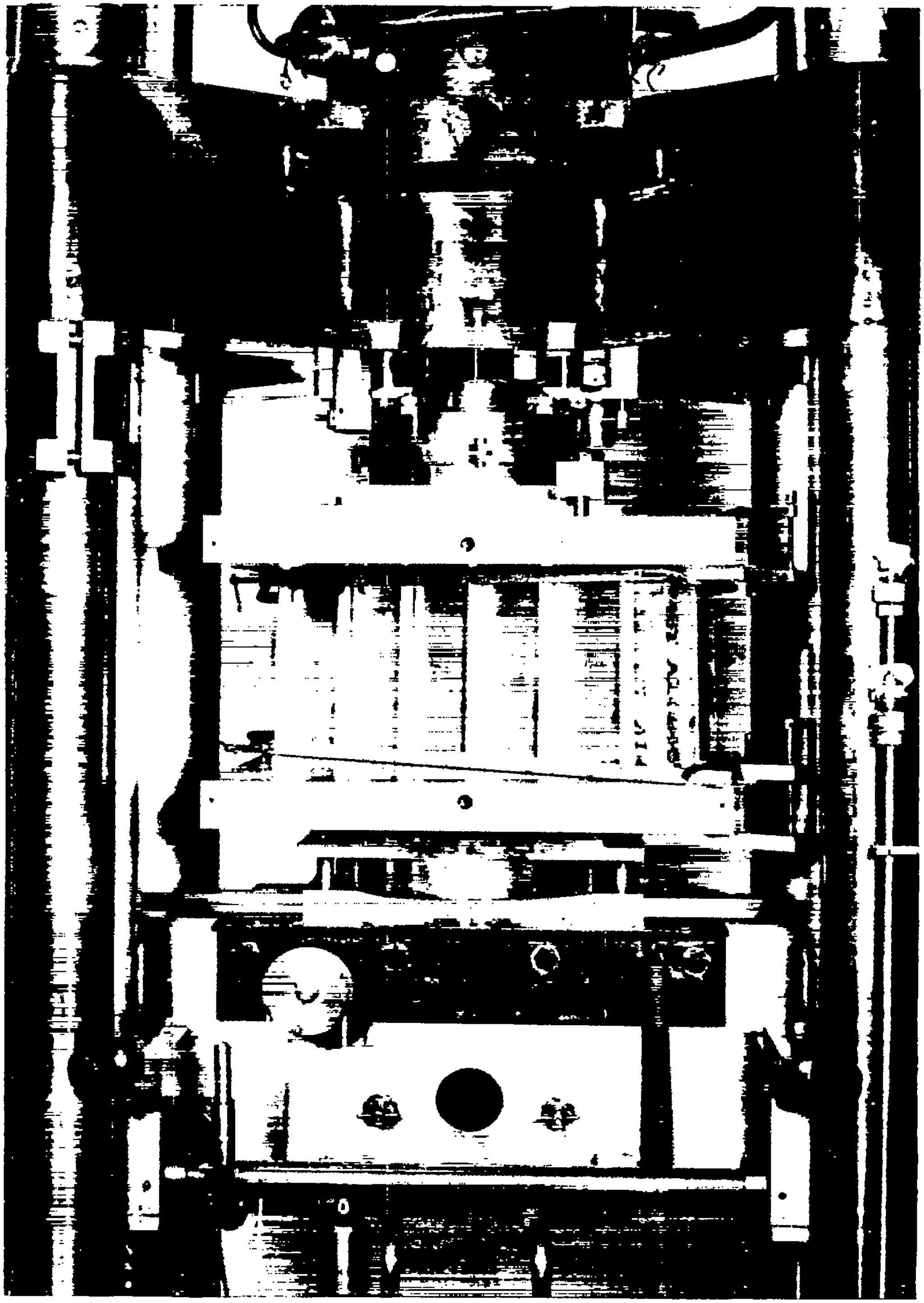


Figure 5.- Arrangement for testing a stiffened-flat-sheet specimen.

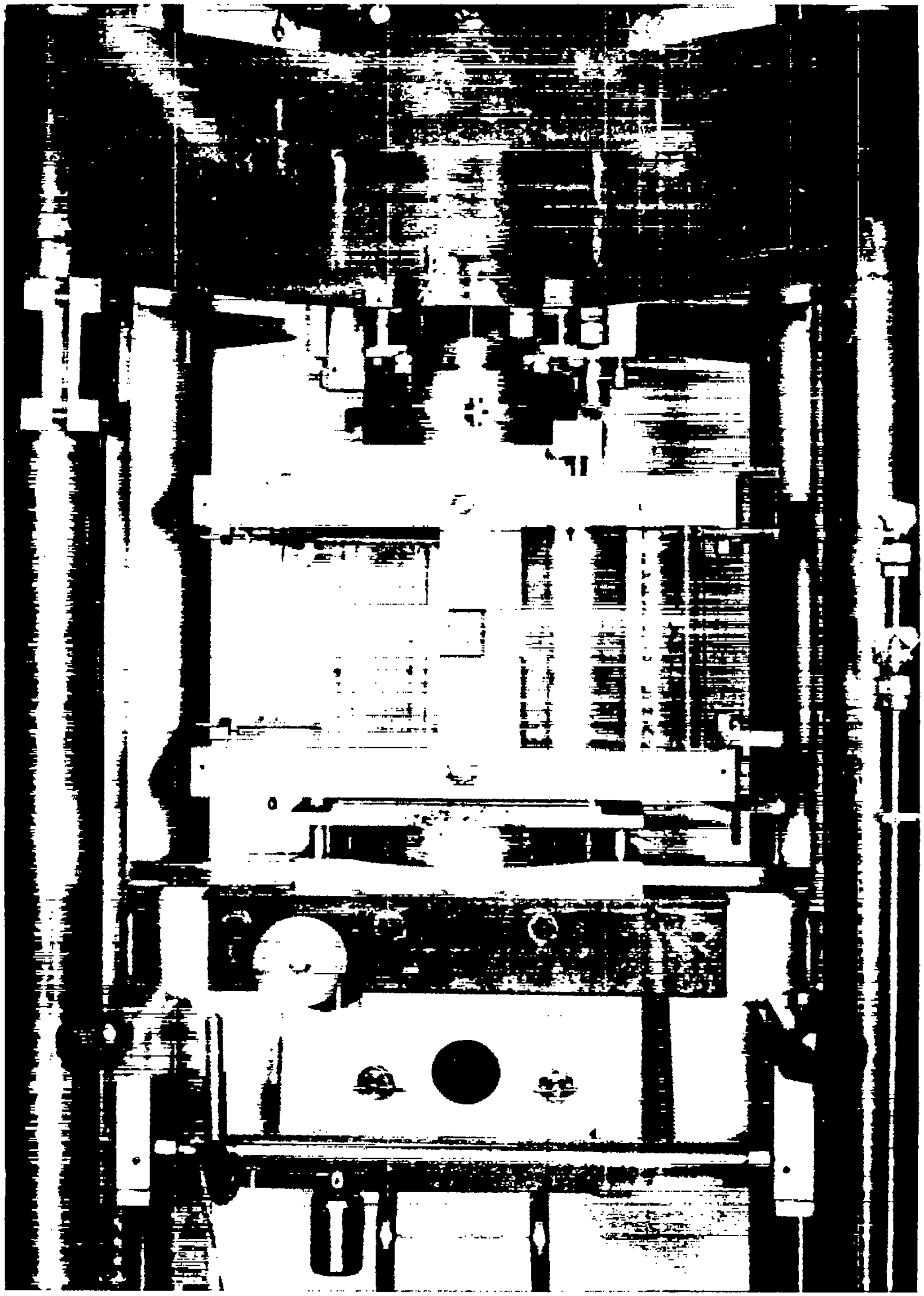


Figure 6.- Arrangement for testing a stiffened-curved-sheet specimen.

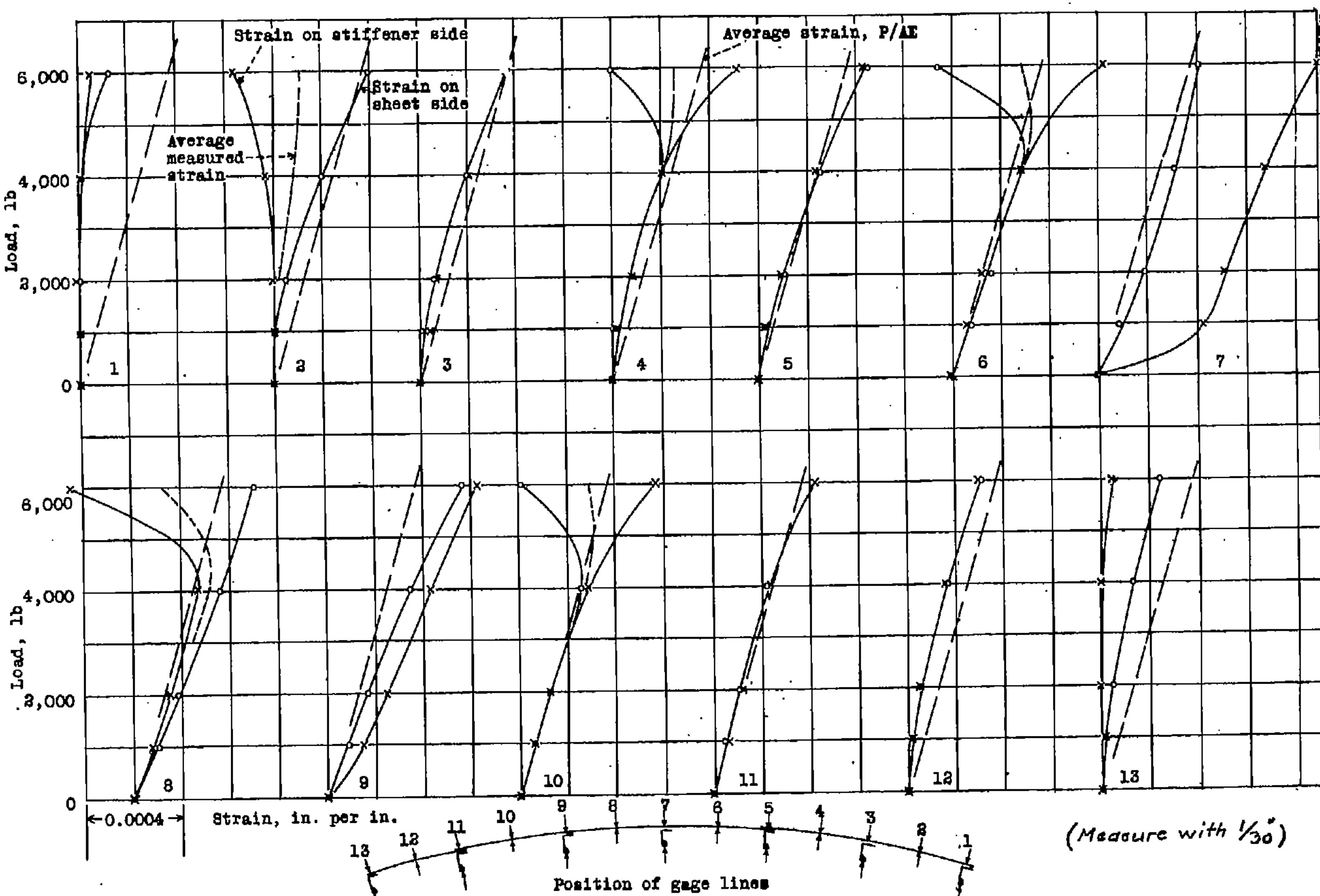


Figure 7.- Relationship between load and measured longitudinal strain for stiffened-curved-sheet. Specimen A; length, 10.625 inches; sheet thicknesses, 0.0275, 0.0295, and 0.0300 inch; radius of curvature, 62 inches.

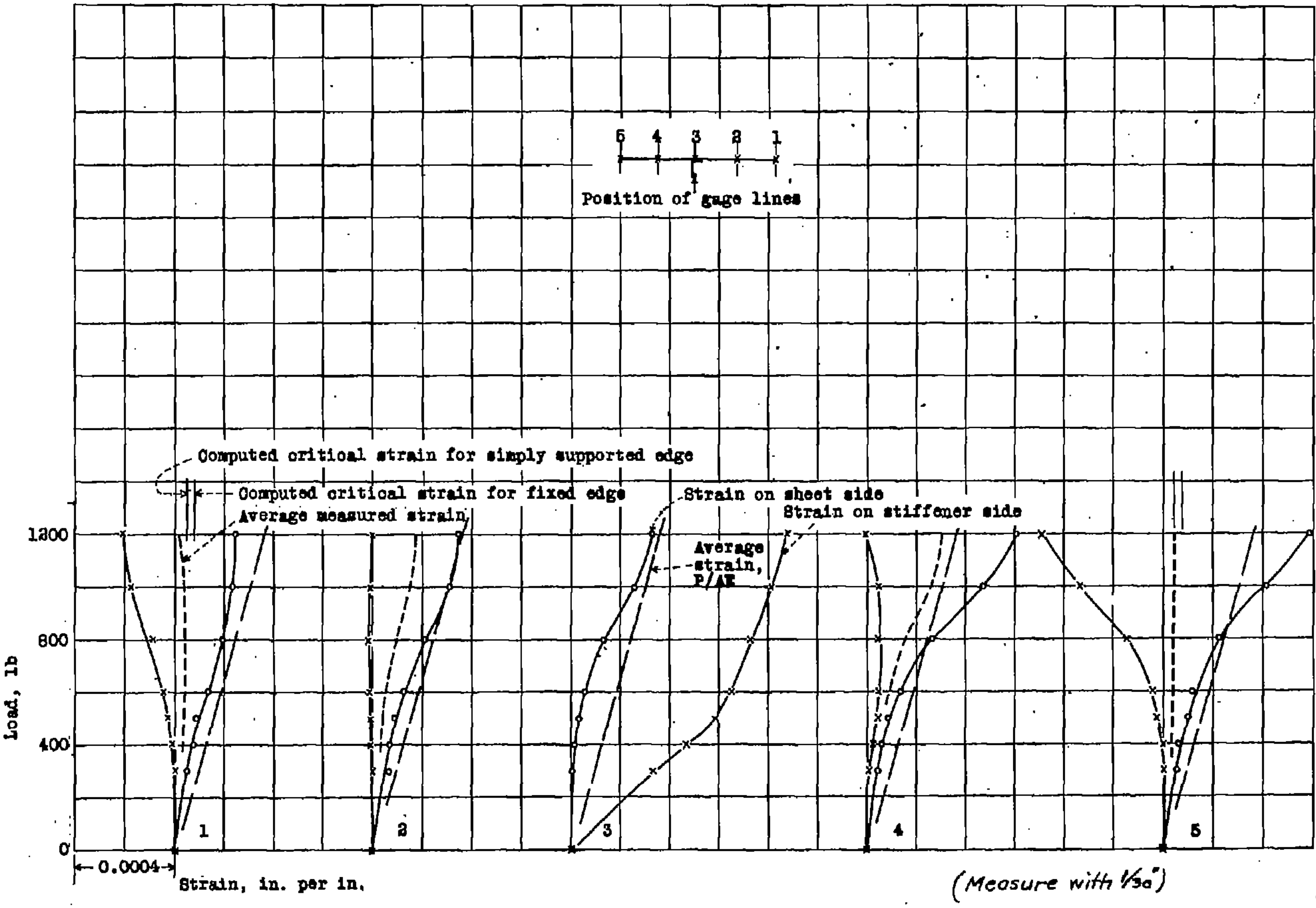
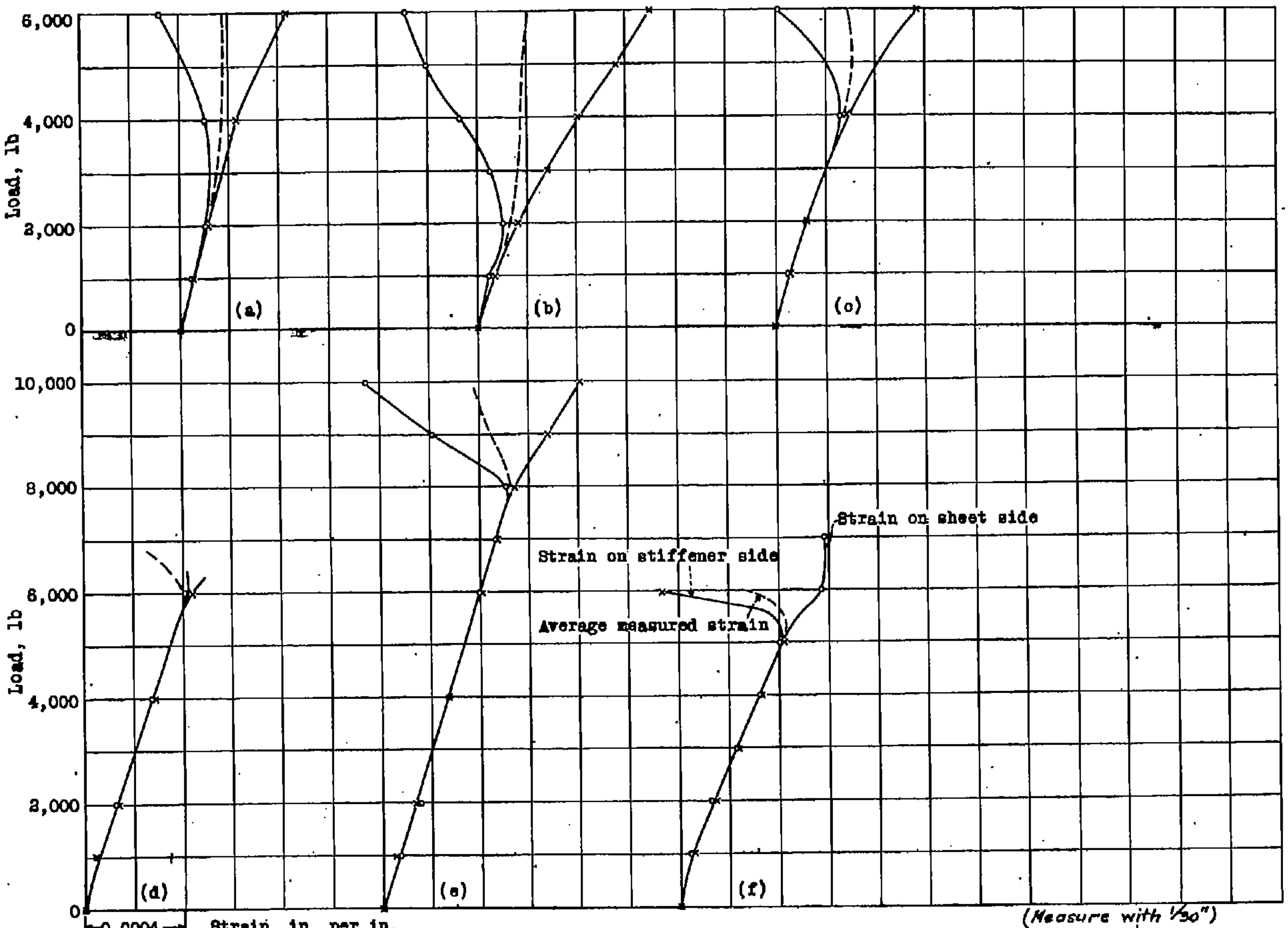


Figure 8.- Relationship between load and measured longitudinal strain for stiffened flat sheet. Specimen D; length, 12.530 inches; sheet thickness, 0.0305 inch; sheet width 8-1/16 inches.



(a) Specimen A, flat sheet. (b) Specimen A', flat sheet. (c) Specimen A, curved sheet; radius of curvature, 62 inches.
(d) Specimen A, curved sheet; radius of curvature, 46.5 inches. (e) Specimen A, curved sheet; radius of curvature, 31 inches.
(f) Specimen A', curved sheet; radius of curvature, 31 inches.

Figure 9.- Relationship between load and longitudinal strain for gage line 10 of specimens A and A' tested as stiffened flat and curved sheet.

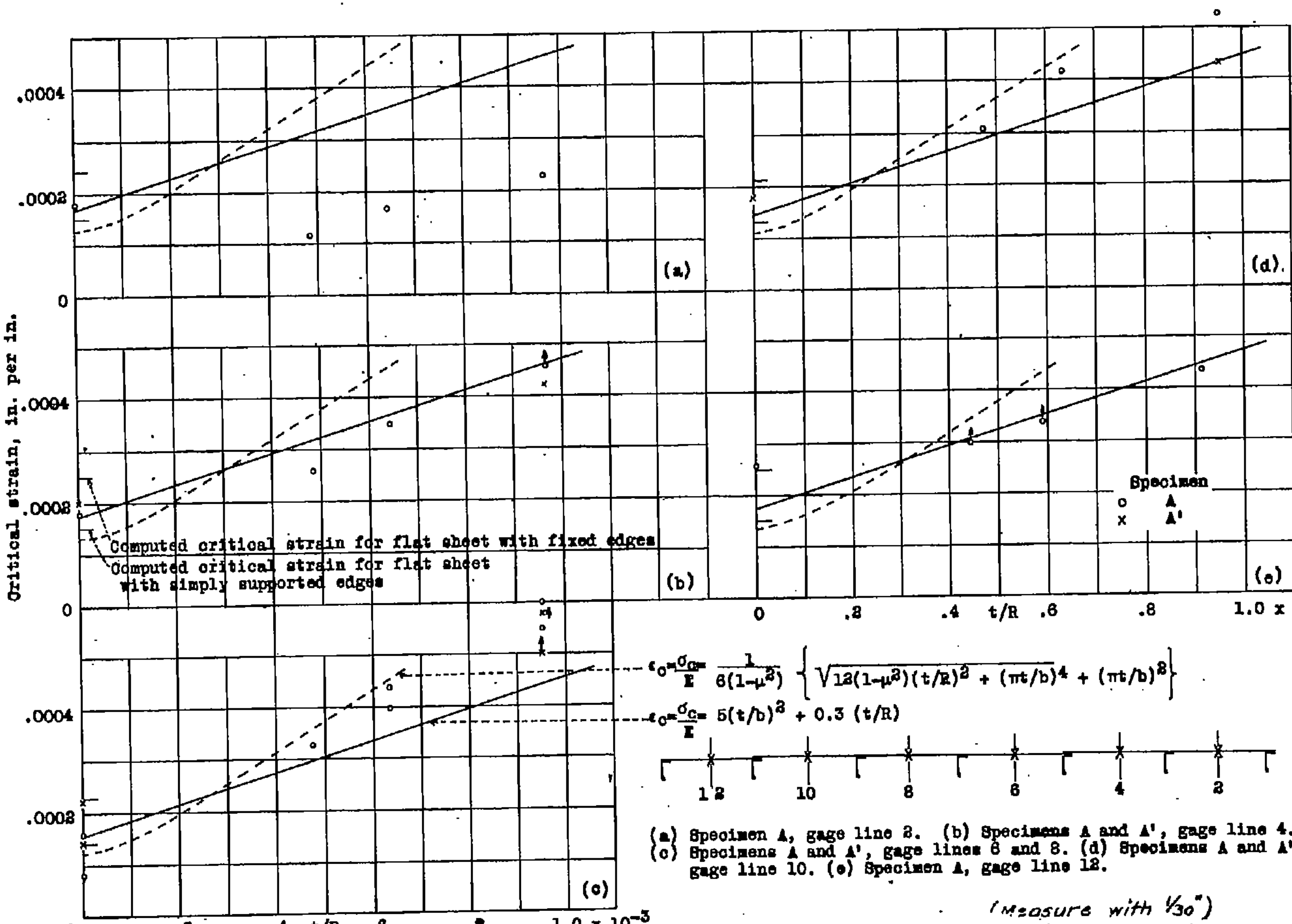


Figure 10.- Effects of curvature on measured critical strain of stiffened sheet.